Opportunities and Challenges in Realizing a Global (Mobile) Military Information Infrastructure

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The vision of a global network-centric tactical military infrastructure is compelling in that it is based on a construct that moves information rapidly from any source to any sink across the military on an as-needed basis: "the right information to the right place at the right time" as it is so often quoted. The realization of the tremendous opportunity offered by such an infrastructure hinges on the resolution of a number of significant engineering challenges; challenges that are manifested by the fact that military networks have characteristics that transcend the current state-of-the-art in networking today, namely that they are built on communication links that are inherently *unpredictable*. This talk presents a framework for addressing some of these challenges in fundamental ways that recognizes this underlying unpredictability of the physical layer and relates it to the achievable Quality of Service (QoS) and the associated complexity of the systems required to manage it. While such a framework ultimately helps researchers, engineers, and program managers make wise technology investment decisions, it is important to build a "technology roadmap" that is ultimately tied to operational capabilities.

Despite many years of financially intensive investments toward the realization of large-scale tactical military networks, relatively little progress has been made especially when compared to those of the commercial networking domain. While the vision of "network centricity" draws heavily and naturally on the apparent ease and ubiquity of the Internet, building a "military Internet" is proving to be much more difficult than the build-out of mobility in the commercial Internet. This is primarily due to the fact that while commercial telecommunication networks are predominantly built on top of wired, relatively stable connections, tactical military networks must cope with fundamentally different underlying operating characteristics, hostile environments, and dynamic link conditions. This, in turn, is due partly to the demanding blend of two historically different engineering disciplines: radio communication engineering and network engineering. While communication engineering has information theory as its foundation, there is no fundamental theory of networks.

If we are to realize large-scale, robust mobile tactical military infrastructure that can truly withstand the rigours of both war and peace, we are faced with the Grand Challenge of the development of a Fundamental Theory of Networks. We simply cannot design, build, and mange networks according to twenty year old methodologies such as strict layered architectures which were developed for highly *predictable* fixed infrastructures. The major challenges in next-generation military communication networks will be a direct consequence of dynamic, *unpredictable* operating conditions.

The guiding objective of architecting tactical military wireless networks must be the *management* of Quality of Service (QoS). QoS, however, must be defined in a much broader sense than traditionally used

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by network engineers. We define the Quality of Service as "*the degree to which the right information is able to be delivered to the right place at the right time*". By defining QoS in this sense, the business of network planning, management, optimization, and operations can collectively be viewed as QoS management. Such a holistic view is necessary to construct a lasting foundation for such disparate, large-scale networks. This is in direct contrast to the strictly-layered approach currently being pursued in military network design simply because it has historically worked so well in the design of commercial infrastructure. The management of QoS must be approached *across* the protocol stack in a deterministic design method. This cross-layer design (CLD) approach has recently been receiving attention in the cellular and mobile *ad hoc* network research areas although with no fundamental framework or guidance.

Predictability is likewise defined as *the measure of the degree to which the state of the network can be reliably observed*. Naturally, fixed-base terrestrial communications are highly predictable; space-based networks are moderately predictable, while tactical mobile networks are the least predictable. This decrease in predictability is due to several factors the most fundamental of which are topological time variance, dynamically changing traffic flows from node-to-node (heterogeneity), and the underlying channel statistics incorporating varying capacities and fading effects.

It is therefore recognized that as the physical layer becomes less predictable, cross-layer coupling and optimizations that exploit "knowledge" of the underlying communication path among the layers is needed. CLD, however, lacks a rigorous theoretical approach but then so does our current large-scale mobile network engineering science. Given a large mobile mesh or *ad hoc* military network, who can say what the achievable end-to-end communication capacity is? Without such knowledge, the objective utility and even viability of a given system design is undeterminable; we simply don't know how good we're doing. We need a bound against which the degree of design optimization can be benchmarked and assessed. Radio science has evolved through benchmarking relative to the point-to-point channel capacity defined by Shannon's Capacity Theorem. However, such a theoretical approach will be impossible for networking if strict layering is not rejected since cross-layer design optimization will be an important element of any theoretical framework.

With this basis, we are now prepared to sketch out a predictability-based framework by recognizing that within a predictability class (low, moderate, high), for any given system, the complexity of a QoS management solution translates to an *achievable* QoS. That is, after a certain level of "QoS complexity" is built into a system design, there are diminishing returns for increasing that level of complexity. This simple recognition can be used to guide investment, network planning, management, and control activities to ensure a more efficient design while not squandering resources.

The visions of Network Enabled Capabilities (NEC) and Network-Centric Warfare (NCW) have become widely accepted yet large-scale realization of next-generation military networks seems increasingly elusive. Without communications, the military "mission" cannot be accomplished; before us stands a tremendous opportunity to change the face of military communications through patience, discipline, and the true application of science.

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The *Grand Challenge:*
Development of a *Fundamental Theory of Networks*

We cannot design, build and manage networks according to 20 year old methodologies (e.g. strictly layered architectures) developed for highly *predictable* fixed infrastructures!

The major challenges in next-generation military communication networks will be a direct consequence of dynamic, *unpredictable* operating conditions

Objective of Tactical Wireless Network Utility: *Management* of QoS

- **Quality of Service (QoS) – *The <u>degree</u> to which the right information is able to be delivered to the right place at the right time.***

- **Utilizing links which are:**
  - **Topologically time varying – especially in the heat of battle!**
  - **Dynamically changing traffic flows from node-to-node (heterogeneous)**
  - **Interconnected via fading channels of varying capacities and channel statistics**

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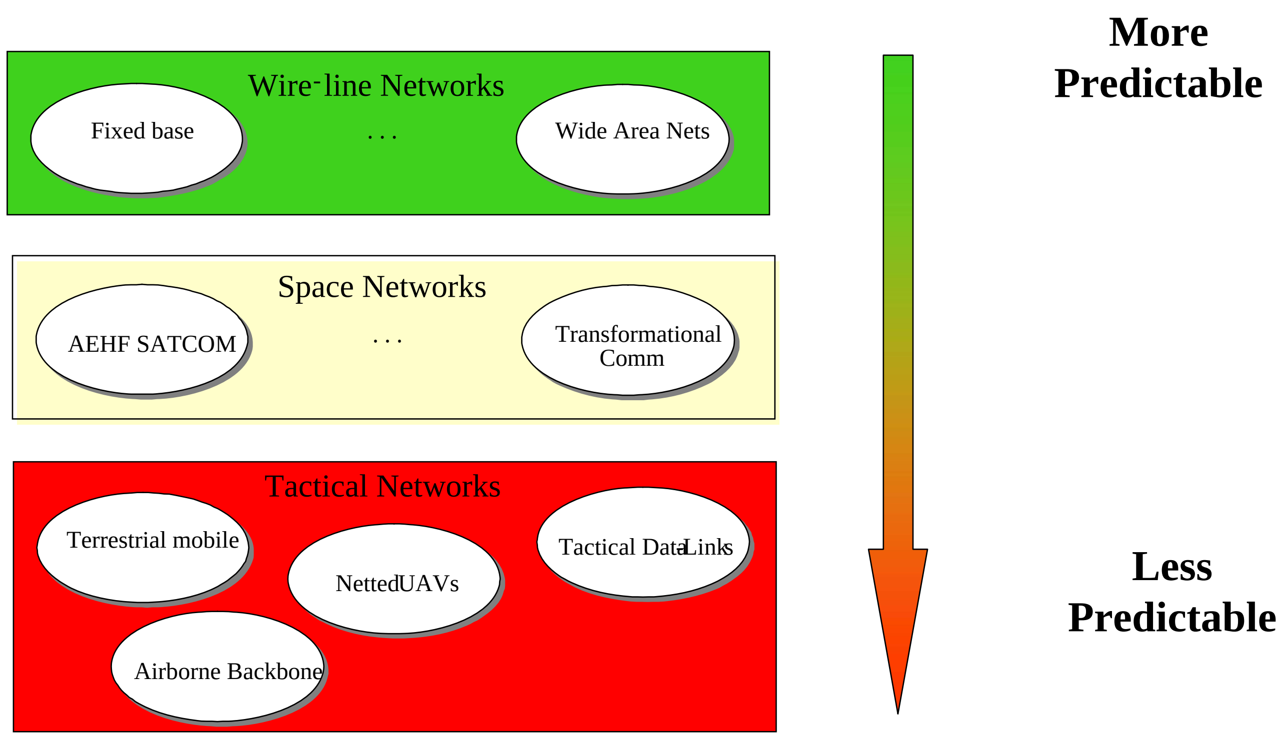
Fundamental Definition: Network Predictability

Predictability – ***a measure of the <u>degree</u> to which the state of the network can be reliably observed***



Resulting Paradigm

- **Peer-to-peer model becomes dysfunctional (strictly layered protocol model fails to exploit inter-layer interactions)**
- **End-to-end network capacity is unknown hence objective utility and even viability of system design is undeterminable**
- **Commercial networking protocols not suited for constrained resources and less predictable physical layers**

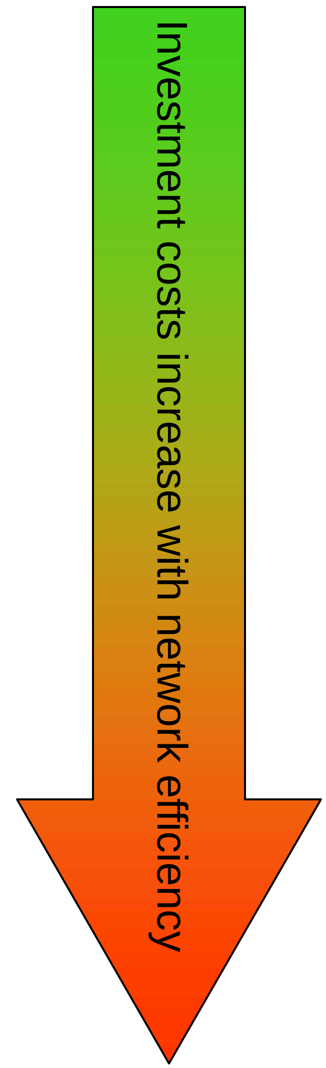
Prevailing Approach to Tactical Network Design

1. **Attempt to leverage commercial network standards (designed for highly predictable fixed infrastructure)**

2. **If that fails, try to modify protocols**

3. **If that fails, develop new protocols**

4. **If that fails … it's time to revisit the layered architecture paradigm**



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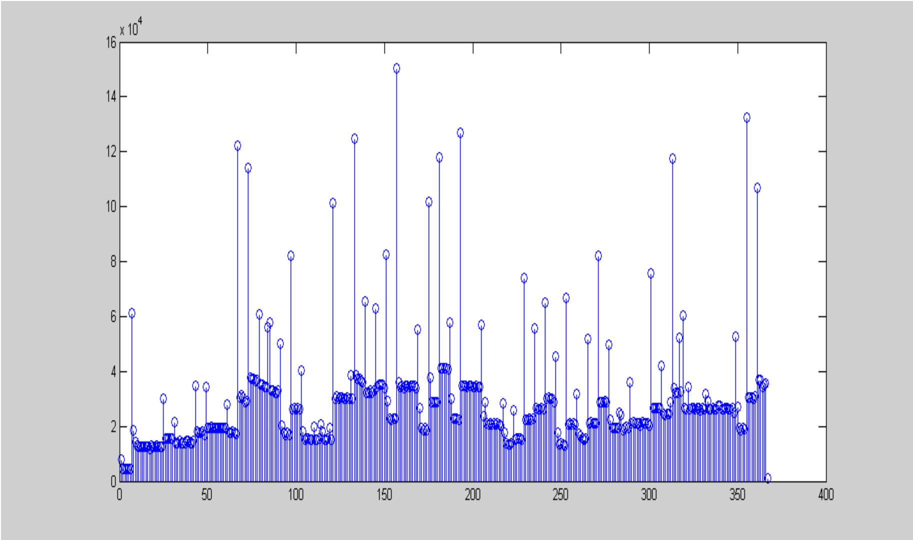
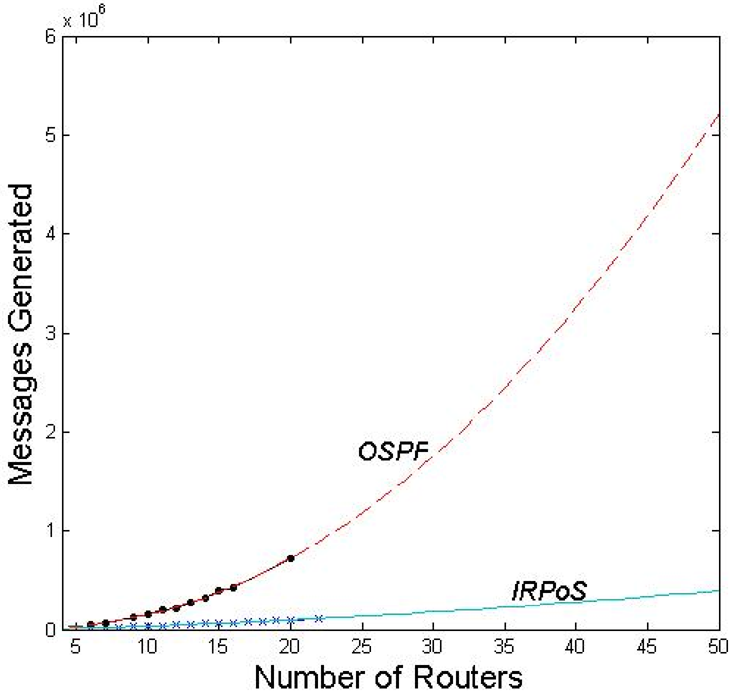
Why Not Protocols designed for Internet-like Environments?

Example: Applying commercial routing protocol to the space domain

Routing overhead versus time



Routing overhead versus network size



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Cross-Layer Design (CLD)

- **When the physical layer becomes less predictable than fixed Internet-like environment, cross-layer coupling and optimizations are needed**
- **The OSI layered reference model (and all others) fail to exploit interactions among layers**
- **CLD is a relatively new, but active, area of R&D … but it lacks a rigorous theoretical approach**

What Do We Need?

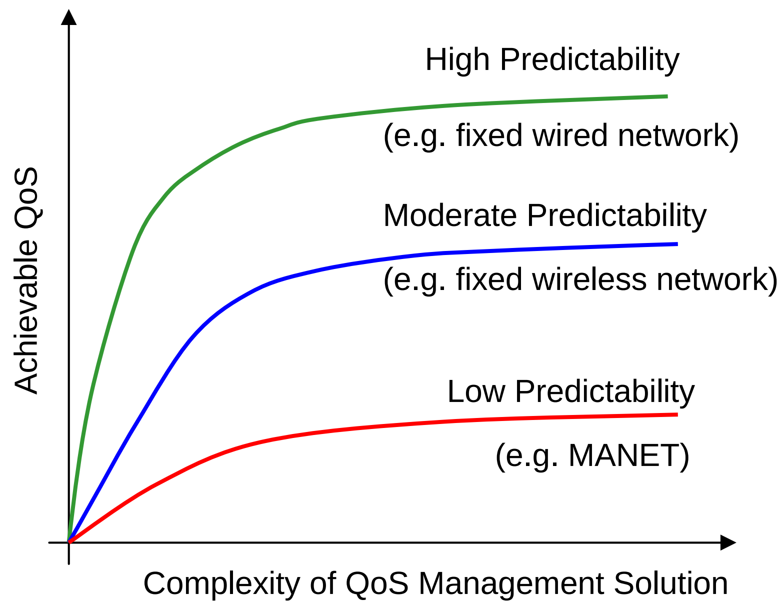
- **A *fundamental theory for communication networks* is needed**
  - **We have nothing analogous to Shannon's theorem for multi-user networks**
  - **Underlying theory is still unknown**
  - **Sets a bound against which degree of design optimization can be benchmarked**
    - **Proper definition of *network* capacity**
- **Such a theoretical approach will be impossible if strict layering is not rejected**
  - **CLD will be an important component in any theoretical framework**

A Proposed Approach

- **Frame the problem as one of *Managing Quality of Service (QoS)***
- **The definition of QoS needs to be broadened substantially**
- **Network management needs to be broadened to become *QoS Management***
  - **Establishes the primacy of network predictability as the dominant factor influencing the manageability of a network**
  - **This framework can be used to guide the decision processes in the planning, investment, architecture and design of next-generation military networks**

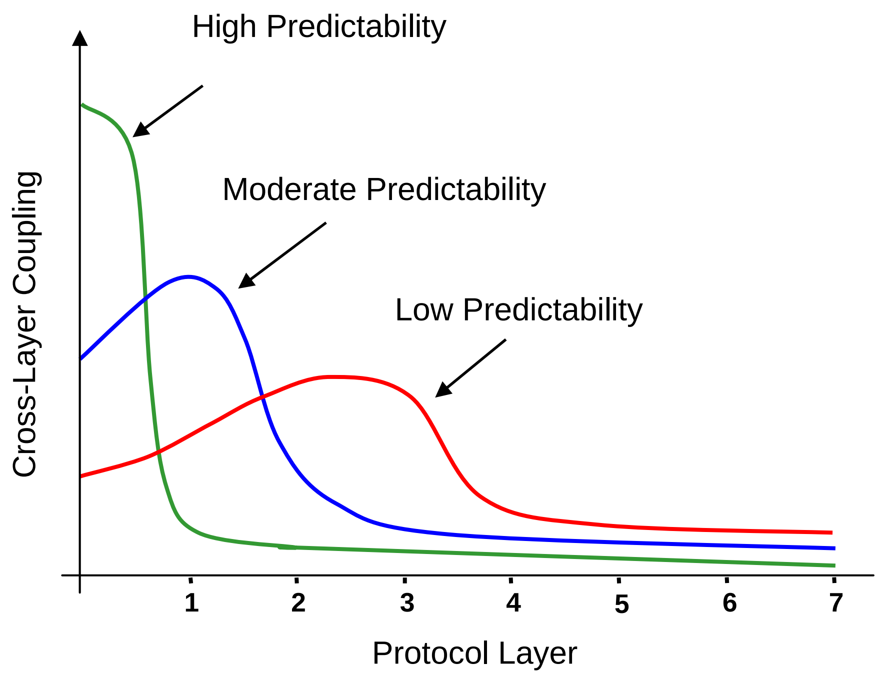
A Predictability-Based Framework

The complexity of a QoS Management solution translates to an *achievable* QoS for various levels of Network Predictability



Using the Framework for CLD

- Each network mode requires a different cross-layer coupling profile to optimize QoS manageability
- Pragmatic approach representing a tradeoff between complexity and inextensibility of monolithic stovepipe systems and the inefficiencies of strictly layered systems



A Proposed Framework for a Technical Investment Roadmap…..

System Capability	Technical Capability	Investment Area	Technology Challenges
Robust Mobile Networking in Dynamic Military Environments	‣ Effective Adaptation of Link, MAC, Network and Application Layers	Cross Layer Design	‣ Development of a Network Theory ‣ Complexity and scalability ‣ Which layers should respond how ‣ Likely not a unified approach across various networks ‣ Needs to include: ‣ Access Scheduling ‣ Route Diversity ‣ Resource Reservation ‣ Network Services Diversity
	‣ Comprehensive Network Management & Control	Mobile Network QoS Management	‣ Resource management & allocation ‣ New distributed approaches that move away from centralized client/server model ‣ Management approach for large numbers of autonomous systems of different characteristics/missions
	‣ Scalability of ad-hoc networks	Multiple Performance Parameters	‣ Designs that are adaptable across several key performance metrics including ‣ Delay/Throughput/Reliability ‣ Power consumption/longevity

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Summary

- Without communications, “the” mission cannot be accomplished
  - Several major network-centric efforts are at substantial (although largely unrecognized) technical risk due to a lack of willingness to accept that fundamental technology development is required
- There is a unique opportunity for advancing science in communications and networking
  - A long-term investment (Patience)
  - We must build on formal methods (Discipline)
  - It’s hard, but not impossible
  - Potential for impact is outstanding